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RESEARCH MEMORANDUM

INVESTIGATION OF TURBINES SUITABLE FOR USE IN A TURBOJET ENGINE WITH HIGH COMPRESSOR PRESSURE RATIO AND LOW COMPRESSOR-TIP SPEED

I - TURBINE-DESIGN REQUIREMENTS FOR SEVERAL ENGINE OPERATING CONDITIONS

By Robert E. English, David H. Silvern, and Elmer H. Davison

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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RESEARCH MEMORANDUM

INVESTIGATION OF TURBINES SUITABLE FOR USE IN A TURBOJET ENGINE WITH HIGH COMPRESSOR PRESSURE RATIO AND LOW COMPRESSOR-TIP SPEED

I - TURBINE-DESIGN REQUIREMENTS FOR SEVERAL ENGINE OPERATING CONDITIONS

2469

By Robert E. English, David H. Silvern, and Elmer H. Davison

SUMMARY

Even though design of a turbine for a turbojet engine for one particular operating condition may result in excellent operation at this single condition, satisfactory operation under all the required conditions is not thereby guaranteed. One existing high-pressure-ratio, single-spool compressor is considered in this report, and there are determined the design requirements imposed on the turbine by the necessity for driving this compressor under the following conditions: take-off, maximum thrust at altitude, altitude cruising at rated rotative speed, altitude cruising with maximum-thrust exhaust-nozzle area, and engine acceleration at 80 percent equivalent design rotative speed.

The following results were obtained: The turbine design requirements for take-off, maximum thrust at altitude, and cruising with maximum-thrust exhaust-nozzle area were nearly identical. If the engine were to be cruised at altitude at rated engine rotative speed, the minimum permissible annular area at the turbine exit and turbine total-pressure ratio were both considerably in excess of the values for take-off and maximum thrust at altitude. At 80 percent of design-equivalent speed, no turbine is capable of driving the compressor under static conditions within the surge characteristics established by compressor test unless some special accelerating feature is introduced into the engine. If as much as 28.6 percent of the compressor air flow can be bled from the compressor exit, the turbine-design requirements to provide engine acceleration at 80 percent of design-equivalent speed are within the turbine-design requirements for take-off, cruising, and maximum thrust at altitude. It was also concluded that if an engine is to be cruised at rated engine rotative speed, the turbine-design requirements for cruising may be sufficiently different from those for other conditions of engine operation that both the cruising and take-off conditions should be considered in design.

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INTRODUCTION

Even though design of a turbine for a turbojet engine for one particular operating condition may result in excellent operation at this single condition, satisfactory turbine aerodynamic performance under all the required conditions is not thereby guaranteed. For example, a turbine designed for take-off may not perform satisfactorily under the cruising conditions. The turbine aerodynamic performance under the cruising condition may be unsatisfactory because either (1) a limit on aerodynamic loading in the rotor prevents the turbine from driving the compressor at the desired rotative speed or (2) even though the turbine will drive the compressor at the desired speed, the turbine efficiency is undesirably low. This limit on aerodynamic loading is reached at high turbine pressure ratios; beyond this limit any further reduction in turbine exit pressure will not affect the forces on the last row of rotor blades. At this limit of aerodynamic loading, an increase in turbine pressure ratio will not produce an increase in turbine equivalent work. Designing within this limit on aerodynamic loading establishes a minimum permissible annular area at the turbine exit in order that the turbine can drive the compressor at desired rotative speed. The sensitivity of turbine efficiency to changes in turbine operating conditions varies from turbine to turbine and depends in a large part on how closely, in the turbine design, the flow conditions approach design limits. In order that during the process of design the turbine designer can consider the various required conditions of engine operation and thereby insure satisfactory turbine performance under the resulting turbine operating conditions, the turbine-design requirements for these various conditions must first be established.

During the process of engine design, an engine operating condition for cruising must be selected. The selection of a mode of engine operation for cruising will affect the turbine-design requirements for cruising. Choice of engine operating condition for cruising should therefore include a consideration of the extent to which a variation in this choice will affect the turbine-design requirements. Whether or not a given variation in turbine-design requirements will have a critical effect on turbine design is not apparent without a turbine-design study.

The use of one existing high-pressure-ratio, single-spool compressor as part of a turbojet engine was investigated at the NACA Lewis laboratory and the turbine-design requirements for driving this compressor as part of a turbojet engine are analyzed herein. The objective of this analysis is to establish the turbine-design requirements imposed on a turbine by the necessity for driving this compressor under the following five conditions:

(1) Take-off

(2) Maximum thrust at altitude

(3) Altitude cruising at rated rotative speed

(4) Altitude cruising with maximum-thrust exhaust-nozzle area

(5) Engine acceleration at 80 percent design equivalent rotative speed, a speed at which compressor surge characteristics commonly limit acceleration

2469 Engine acceleration was analyzed on the basis of bleeding air from the compressor exit as well as the normal engine operation. The variation in the turbine-design requirements is expressed herein as a variation in the following turbine-design parameters: turbine total-pressure ratio, blade-jet speed ratio, and minimum permissible annular area at the turbine exit. In addition to these turbine-design parameters, the variation in the exhaust-nozzle area was also determined.

The effect of the turbine-design requirements for these operating conditions on the problem of turbine design is a topic to be treated in subsequent phases of this investigation.

For the critical study of an actual engine, selection of the operating condition for cruising will include a consideration of the operating condition which results in the minimum specific fuel consumption at the desired thrust level. For a preliminary design study such as this one, the turbine-efficiency contours cannot be accurately forecast; therefore the exact operating condition resulting in minimum specific fuel consumption is currently not predictable. Because the operating condition resulting in minimum specific fuel consumption will generally lie between the two cruising conditions which were selected, the turbine-design requirements for minimum specific fuel consumption will lie between those determined for the two selected cruising conditions.

The compressor chosen for this study has high mass flow per unit of frontal area (25.8 lb/(sec)(sq ft)), high over-all pressure ratio (8.75), and low blade-tip speed (892 ft/sec). A severe turbine-design problem is therefore imposed. The over-all performance characteristics of this compressor are presented in reference 1.

For all operating conditions except engine acceleration, the minimum permissible annular area at the turbine exit was considered to be the area that results in operation of the last rotor-blade row at its loading limit; the nature of this loading limit is discussed in reference 2. For engine acceleration, the minimum permissible annular area at the turbine exit was taken equal to either the area for limiting loading or the exhaust-nozzle area, whichever was larger. For the entire analysis, the turbine internal efficiency was assumed to be 0.85.

SYMBOLS

The following symbols are used in this report:

B trailing-edge blockage, $\dfrac{t}{s \sin \beta}$

k fraction of compressor air flow bled at compressor exit

N rotative speed, percent design speed 2469

p pressure (lb/sq ft)

R gas constant (ft-lb/(lb)($^{\circ}$R))

s blade spacing (ft)

T temperature ($^{\circ}$R)

t trailing-edge thickness (ft)

w weight flow (lb/sec)

β rotor-blade exit angle measured from direction of blade motion (deg)

γ ratio of specific heats

δ ratio of pressure to 2116 pounds per square foot

θ ratio of temperature to 518.4° R

Subscripts:

1 compressor inlet

2 compressor exit

3 turbine inlet

4 turbine exit

5 exhaust-nozzle exit

Superscripts:

$'$ total, or stagnation, state

ANALYSIS

Using the over-all compressor characteristics presented in reference 1, a cycle analysis was made of equilibrium engine operation.

Assigned Conditions

2469 The following conditions were assigned for the five engine operating conditions to be considered:

Take-off	
Percentage equivalent design rotative speed, $N/\sqrt{\theta_1'}$	100
Compressor pressure ratio, p_2'/p_1'	8.75
Turbine-inlet temperature, T_3', $^{\circ}R$	2160
Flight Mach number	0
Altitude, ft	0
Maximum thrust at altitude	
Percentage design rotative speed, N	100
Turbine-inlet temperature, T_3', $^{\circ}R$	2160
Flight Mach number	0.75
Altitude, ft	35,000
Altitude cruising at design rotative speed	
Cruising thrust (0.64 of maximum thrust), lb	2310
Flight Mach number	0.75
Altitude, ft	35,000
Altitude cruising with maximum-thrust exhaust-nozzle area	
Cruising thrust, lb	2310
Flight Mach number	0.75
Altitude, ft	35,000
Engine acceleration at 80 percent equivalent design rotative speed	
Compressor pressure ratio, p_2'/p_1'	4.15
Flight Mach number	0
Altitude, ft	0

Assumed Conditions

The following conditions were assumed to exist for the five operating conditions:

Ram efficiency	1.00
Burner total-pressure ratio, p_3'/p_2'	0.95
Turbine internal efficiency	0.85
Exhaust-nozzle efficiency	0.96
Ratio of specific heats in compressor, γ_1	1.40
Ratio of specific heats in turbine, γ_3	1.33
Gas constant in compressor, R_1, ft-lb/(lb)(°R)	53.34
Gas constant in turbine, R_3, ft-lb/(lb)(°R)	53.40

The turbine equivalent weight flow $\frac{w_3\sqrt{\theta_3'}}{\delta_3'}$ was assumed to be constant; 2469
this implies that the turbine stator is choked for all conditions analyzed. The air flow through the compressor was assumed equal to the gas flow through the turbine except for the case of engine acceleration with compressor-exit bleed.

Compressor Characteristics

For the region of greatest interest on the compressor map (over 85 percent of equivalent design speed) only one speed line was experimentally determined in reference 1. In order to provide additional lines, the data of reference 1 were cross-plotted as the variation in choking weight flow with speed. The choking flow was then read from this plot for equivalent speeds of 90, 95, and 108 percent of equivalent design speed. (For flight conditions at an altitude of 35,000 ft and Mach number of 0.75, design rotative speed is 108 percent of equivalent-design speed.) These choking weight flows were used to locate the maximum flow for the additional speed lines in figure 1, and the remaining portions of the speed lines and efficiency contours were faired in by judgment. At 108 percent of equivalent design speed, the surge limit was assumed to lie outside the operating range to be analyzed.

Engine Operation on Compressor Map

The assumption that the compressor air flow equals the turbine gas flow permits the following equation to be written:

$$\frac{w_1\sqrt{\theta_1'}}{\delta_1'} = \frac{p_2'}{p_1'}\sqrt{\frac{T_1'}{T_3'}}\left(\frac{w_3\sqrt{\theta_3'}}{\delta_3'} \times \frac{p_3'}{p_2'}\right) \tag{1}$$

where $\frac{w_3\sqrt{\theta_3'}}{\delta_3'}$ and $\frac{p_3'}{p_2'}$ are both assumed to be constant. For a given flight condition, T_1' is constant. Thus, for each of the five engine operating conditions to be analyzed, lines of constant turbine-inlet temperature T_3' on the compressor map are straight and pass through the origin.

Two constant turbine-inlet temperature lines are plotted on the compressor map in figure 2 for engine operation under static sea-level conditions. The value of the turbine equivalent weight flow $\frac{w_3\sqrt{\theta_3'}}{\delta_3'}$ was so selected that the 2160° R line passes through the operating point specified for take-off, namely, 100 percent of equivalent design speed and a compressor pressure ratio of 8.75. For this equivalent turbine weight flow, the turbine-inlet temperature under the specified conditions for engine acceleration (80 percent of equivalent design speed and a compressor pressure ratio of 4.15) without compressor-exit bleed is 1100° R. The take-off and engine-acceleration conditions are represented in this figure by two dots.

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Lines of constant turbine-inlet temperature T_3' are superimposed on the compressor map in figure 3 for engine operation under the assigned altitude and flight Mach number; these lines were also drawn in accordance with equation (1). The three dots on this map represent the following engine operating conditions: maximum thrust at altitude, altitude cruising at design rotative speed, and altitude cruising with maximum-thrust exhaust-nozzle area.

Limiting Blade Loading and Minimum Permissible Annular Area at Turbine Exit

As stated in the INTRODUCTION, the minimum permissible annular area at the turbine exit is considered to be the annular area resulting in operation of the last rotor-blade row at its loading limit for all cases of engine operation analyzed except for engine acceleration under static sea-level conditions. The mechanism of limiting blade loading is discussed and analyzed in reference 2. The manner in which limiting blade loading affects engine operation and turbine design may be summarized as follows:

The problem of decreasing the thrust of a turbojet engine from its maximum value while maintaining the engine rotative speed constant is considered. In order to decrease engine thrust, the fuel flow can be adjusted to reduce the turbine-inlet temperature. The turbine total-pressure ratio must be increased by opening the exhaust nozzle to prevent the engine rotative speed from decreasing. Increasing the exhaust-nozzle area raises the axial Mach number in the annulus at the turbine exit. Whenever the engine thrust is continually decreased by continually decreasing turbine-inlet temperature and increasing exhaust-nozzle area, an engine operating condition is eventually reached beyond which any further reduction in turbine-inlet temperature will produce a decrease in engine rotative speed despite any increase in the exhaust-nozzle area. This phenomenon occurs even if the ram pressure ratio is sufficiently high so as to maintain choking of the exhaust nozzle and is herein referred to as "limiting blade loading".

Limiting blade loading, as investigated and evaluated in reference 2, applies to blade rows having interblade channels that converge to a throat and have no divergence after the throat. This configuration is typical of turbine blading. Although the limitation on blade loading can be increased beyond the limit in reference 2 by employing channels 2469 that diverge as well as converge, this is generally not desirable in aircraft gas turbines. For this reason, the blade loading limit analyzed in reference 2 is employed in this analysis.

The results of the analysis in reference 2 were applied in order to determine the flow conditions downstream of the last rotor-blade row at the point of limiting loading. Between the throat in the rotor-blade passage and a station downstream of the rotor at which the flow conditions are uniform, the flow was assumed to be isentropic. The axial Mach number at which limiting loading occurs is shown in figure 4 for two values of trailing-edge blockage, which is defined as follows:

$$B \equiv \frac{t}{s \sin \beta} \tag{2}$$

For blade-exit angles typical of rotor blades, that is, between 30° and 60°, and trailing-edge blockage from 0.05 to 0.10, the axial Mach number has only small variations with blade-exit angle. For the purposes of this analysis, limiting blade loading was assumed to occur with an exit axial Mach number of 0.70. For those operating conditions that result in both a supercritical pressure ratio across the exhaust nozzle and close to zero whirl at the turbine exit, the minimum permissible annular area at the turbine exit is directly proportional to the exhaust-nozzle area; within the conditions assumed for this analysis, the minimum permissible annular area at the turbine exit is 6.7 percent larger than the exhaust-nozzle area if the exhaust nozzle is choked.

Engine Acceleration

Engine operation near the "knee" of the surge line in figure 2, that is, near 80 percent of equivalent design speed, very likely constitutes a critical condition for engine acceleration. Several variations in the engine may be considered to improve the rate of acceleration if a satisfactory rate of acceleration is not obtainable with a fixed-geometry turbine and a wide-open exhaust-nozzle:

(1) Change the loading distribution among the stages in the compressor and thereby change the compressor performance and the shape of the surge line

(2) Bleed air at the compressor exit

(3) Bleed air from the compressor at a point midway along its length

(4) Provide turbine-stator adjustment (See reference 3.)

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Of these methods of increasing the rate of acceleration only bleeding air at the compressor exit is analyzed.

For engine acceleration under the two conditions of operation, that is, with and without compressor-exit bleed, the turbine pressure ratio required to drive the compressor was determined and using this ratio the required exhaust-nozzle area was then computed. The compressor-surge characteristics are assumed to be those shown in figure 1 although the compressor characteristics in figure 1 were determined by component test.

For compressor-exit bleed, equation (1) was modified to read

$$(1-k)\,\frac{w_1\sqrt{\theta_1'}}{\delta_1'} = \frac{p_2'}{p_1'}\sqrt{\frac{T_1'}{T_3'}}\left(\frac{w_3\sqrt{\theta_3'}}{\delta_3'} \times \frac{p_3'}{p_2'}\right) \tag{3}$$

For engine acceleration without compressor-exit bleed, k is, of course, zero and T_3' is 1100° R. By simultaneously varying k and T_3' in this equation, all other terms in the equation may be maintained constant. Engine acceleration was analyzed using

$$(1-k)^2\, T_3' = 1100^\circ \text{ R} \tag{4}$$

For the single value of compressor-exit bleed considered in this analysis, the turbine-inlet temperature T_3' was assigned the value of 2160° R; for this condition, k equals 0.286 in order to satisfy equation (4). By varying k and T_3' in accordance with equation (4), the operating point in figure 2 for engine acceleration at 1100° R with no compressor-exit bleed also represents the operating point with a turbine-inlet temperature of 2160° R and a k of 0.286.

RESULTS

The results of the analysis of engine operation at altitude are presented in figure 5. These curves represent all practicable operating points; that is, all practicable combinations of turbine-inlet temperature, engine speed, and exhaust-nozzle area. The variation in engine thrust, turbine blade-jet speed ratio, turbine total-pressure ratio, minimum permissible area at the turbine exit, and exhaust-nozzle area with percent of design-equivalent speed and turbine-inlet total temperature are shown. The maximum thrust for these flight conditions is 3600 pounds. The characteristics in figure 5 have been replotted in figure 6 in order to show the variation in the turbine parameters between cruising and maximum thrust for the two types of cruising operation selected earlier.

The values of the turbine parameters and the exhaust-nozzle area for the five conditions of engine operation are listed in table I along 2469
with some compressor and engine parameters. The turbine total-pressure ratio, blade-jet speed ratio, and minimum permissible annular area at the turbine exit have only minor variations between take-off, maximum thrust at altitude, and altitude cruising with maximum-thrust exhaust-nozzle area. In contrast with these three conditions of operation, the turbine total-pressure ratio and minimum permissible annular area at the turbine exit are markedly increased for altitude cruising at rated engine speed; the blade-jet speed ratio increases to a smaller extent. In order to produce maximum thrust at altitude, the exhaust-nozzle area varies only slightly from the area required for take-off; this small variation in exhaust-nozzle area also applies, of course, to altitude cruising with maximum-thrust exhaust-nozzle area. In contrast with this phenomenon, the exhaust-nozzle area must be increased by 21 percent in order to cruise at altitude at rated rotative speed.

For equilibrium operation of the engine at 80 percent of equivalent design speed without compressor-exit bleed, a turbine total-pressure ratio of 4.45 is required (table I) if the turbine is to produce enough power to drive the compressor, whereas the compressor total-pressure ratio is only 4.15. For this reason, no turbine can drive the compressor under normal conditions (ram pressure ratio = 1) at 80 percent equivalent design speed without some auxiliary starting device.

On the other hand, if the turbine-inlet temperature is increased to 2160° R, 28.6 percent of the compressor air flow must be bled off at the compressor exit in order to maintain the compressor pressure ratio at a value of 4.15. The flow area theoretically required to bleed off 28.6 percent of the air at the compressor exit is 27.3 square inches. With the engine operating under this condition, the turbine total-pressure ratio is reduced to 2.73, well within the compressor total-pressure ratio of 4.15. For the exhaust nozzle, a total-static pressure ratio p_4'/p_5 of 1.44 is available for expelling the exhaust gas from the engine. For this pressure ratio the exhaust-nozzle area is 311 square inches, well below the exhaust-nozzle area for take-off. Thus, with compressor-exit bleed the turbine is capable of driving the compressor under equilibrium operation (no acceleration).

However, rapid acceleration is desired. An estimate was made of the turbine-work output with the exhaust-nozzle area increased above the 311-square-inch area required for equilibrium operation. With the exhaust-nozzle area increased to the take-off value of 359 square inches, the turbine-power output increases by 3.5 percent over the compressor-power requirement. In order to obtain a 10-percent excess of power, the exhaust-nozzle area must be increased to 420 square inches, a 17-percent increase over the take-off value. The entire amount of these excesses of turbine power will very likely be difficult to obtain in practice because the turbine internal efficiency may not be as high as the assumed value of 0.85; the turbine will be operating at a considerable distance from its design point, having both pressure ratio and blade-jet speed ratio less than the design values (see table I). The computed excess of turbine power over compressor power is a hedge against low turbine efficiency.

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DISCUSSION OF RESULTS

The mode of engine operation selected for cruising has a prominent effect on the turbine-design requirements (table I). If the engine is to be cruised at altitude with the maximum-thrust exhaust-nozzle area, the turbine-design requirements for take-off, cruising, and maximum thrust at altitude are almost identical. A turbine designed for one of these three operating conditions should therefore perform satisfactorily under the other two conditions. On the other hand, if the engine is to be cruised at altitude at rated engine speed, the turbine pressure ratio and minimum permissible annular area at the turbine exit for cruising are both considerably greater than the take-off values. The necessity for a large exit annular area complicates the problem of obtaining a satisfactory turbine design within a given number of turbine stages which has satisfactory performance under the take-off and maximum-thrust-at-altitude conditions because with a large annular area the designer may have difficulty staying within the employed limits on Mach number, turning, and static-pressure change; even if these limits are not exceeded, the design becomes more critical in this regard. Despite the increase in blade-jet speed ratio between take-off and cruising at rated engine speed, operation of a given turbine at the higher turbine pressure ratio may increase the leaving loss associated with tangential velocity at the turbine exit; avoiding this loss at cruising while maintaining a given number of turbine stages will require a turbine design having less reaction at the conditions of take-off and maximum thrust at altitude. These aerodynamic design problems can, of course, be considerably simplified by incorporating additional turbine stages in the design.

From these results, it can be concluded that if this engine is to be cruised at rated engine rotative speed, the turbine-design requirements for cruising are sufficiently different from those for other conditions of engine operation that both the cruising and take-off conditions should be considered in design.

Altitude cruising at rated engine speed may also introduce problems associated with afterburner design because the afterburner-entrance velocity will have fairly wide variations between the maximum-thrust and cruising conditions of operation. Under the cruising condition, the 2469 turbine-exit axial Mach number will probably be near the limiting value of 0.70. In order that inordinate friction pressure losses will not occur in the afterburner under cruising conditions, the internal aerodynamic characteristics of the afterburner must be such that without burning in the afterburner only small losses in pressure are obtained at entrance Mach numbers as high as 0.70.

An exact determination of the turbine-design requirements for engine acceleration is difficult to make for two reasons:

(1) The compressor surge characteristics with the compressor as part of the engine will probably be different from those determined by compressor test.

(2) The turbine efficiency cannot be accurately predicted at this off-design point.

On the basis of the results of this analysis, turbine-design requirements for engine acceleration are within the turbine-design requirements for take-off, maximum thrust at altitude, and cruising at altitude.

SUMMARY OF RESULTS

The problem associated with designing a turbine for several conditions of jet-engine operation was investigated by determining the design requirements for a turbine to drive a particular high-pressure-ratio, single-spool compressor for five conditions of engine operation. An evaluation of the effect of these design requirements on turbine design requires a turbine-design study, which is beyond the scope of this report. The following results were obtained:

1. The turbine-design requirements for take-off, maximum thrust at altitude, and cruising with maximum-thrust exhaust-nozzle area were nearly identical.

2. If the engine was to be cruised at altitude at rated engine rotative speed, the minimum permissible annular area at the turbine exit and turbine total-pressure ratio were both considerably in excess of the values for take-off and maximum thrust at altitude.

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3. At 80 percent of design equivalent speed, no turbine was capable of driving the compressor under static conditions within the surge characteristics established by compressor test unless some special accelerating feature was introduced into the engine.

4. If as much as 28.6 percent of the compressor air flow can be bled from the compressor exit, the turbine-design requirements to provide engine acceleration at 80 percent of design equivalent speed were within the turbine-design requirements for take-off, cruising, and maximum thrust at altitude.

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CONCLUSION

If an engine is to be cruised at rated engine rotative speed, the turbine-design requirements for cruising may be sufficiently different from those for other conditions of engine operation that both the cruising and take-off conditions should be considered in turbine design.

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2. Hauser, Cavour H., and Plohr, Henry W.: Two-Dimensional Cascade Investigation of the Maximum Exit Tangential Velocity Component and Other Flow Conditions at the Exit of Several Turbine-Blade Designs at Supercritical Pressure Ratios. NACA RM E51F12, 1951.

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TABLE I - TURBINE AND ENGINE PARAMETERS FOR FIVE OPERATING CONDITIONS

	Take-off[a]	Maximum thrust at altitude[b]	Altitude cruising with maximum-thrust exhaust-nozzle area[b]	Altitude cruising at rated rotative speed[b]	Engine acceleration at 80 percent equivalent design speed[a]	
					No bleed	Bleed 28.6%
Turbine total-pressure ratio	3.42	3.33	3.30	4.24	4.45	2.73
Blade-jet speed ratio	0.318	0.320	0.311	0.340	0.328	0.277
Minimum exit annular area (sq in.)	383	373	373	460	-----	314
Turbine-inlet temperature, (°R)	2160	2160	1690	1620	1100	2160
Compressor total-pressure ratio	8.75	10.07	7.72	8.74	4.15	4.15
Percentage design speed	100	100	86.6	100	80	80
Percentage equivalent design speed	100	108	93.5	108	80	80
Exhaust-nozzle area (sq in.)	359	350	350	433	-----	311
Compressor-inlet temperature, (°R)	518.4	437.9	437.9	437.9	518.4	518.4
Engine thrust, (lb)	10360	3600	2310	2310	-----	-----

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[a]Take-off and engine acceleration were under static sea level conditions.

[b]Altitude operation was at an altitude of 35,000 feet and flight Mach number of 0.75.

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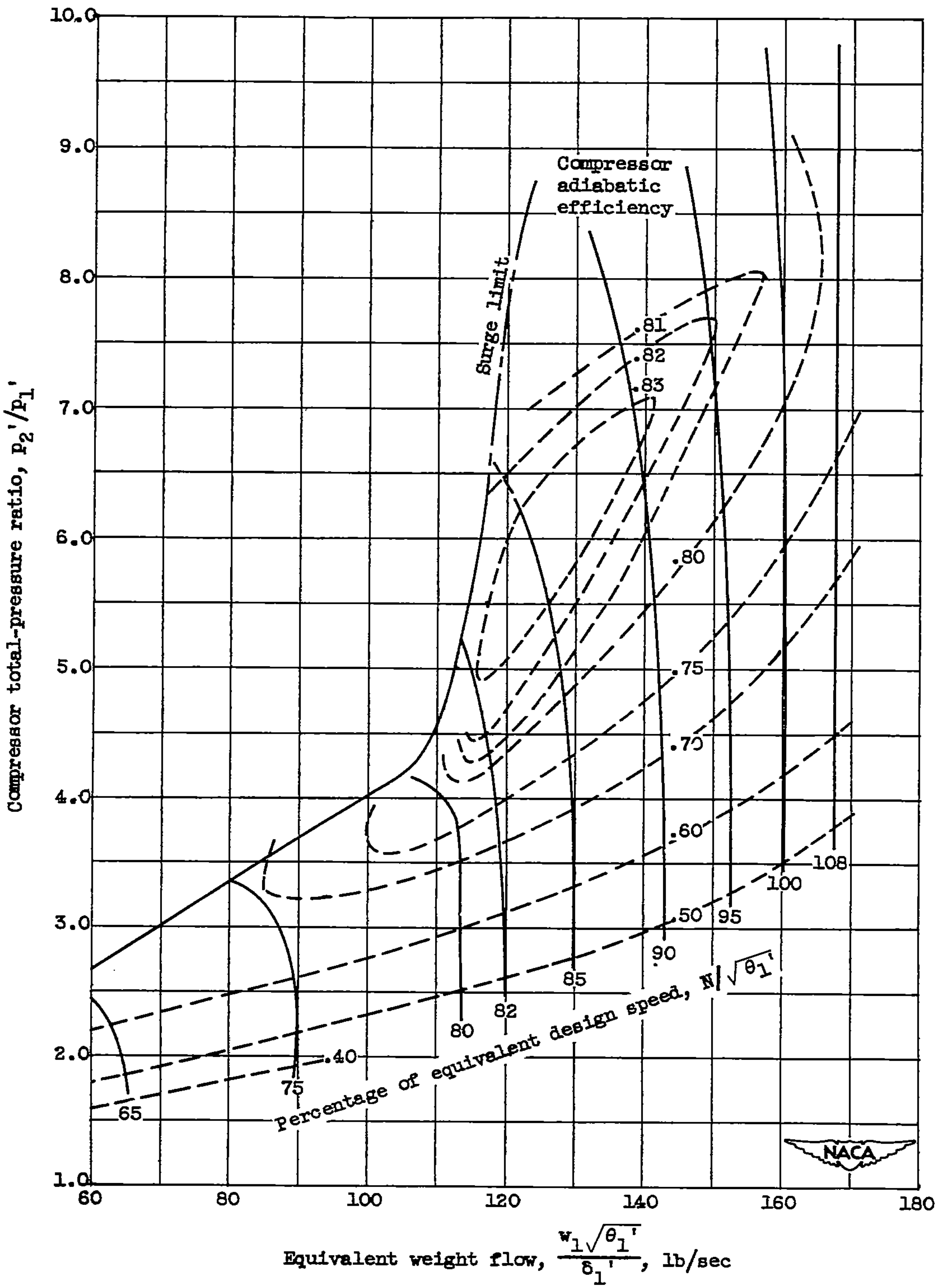

Figure 1. - Extended performance of compressor.

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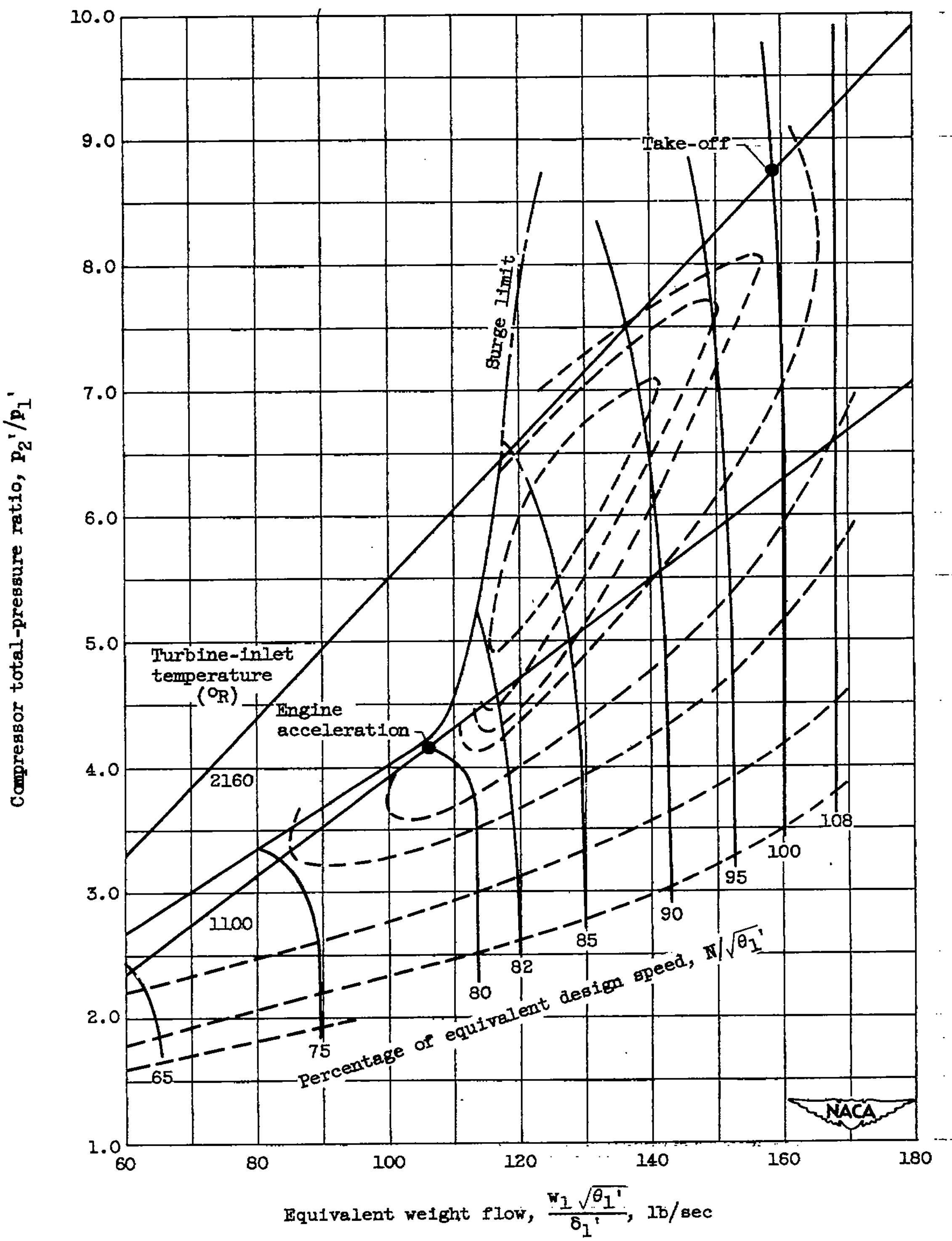

Figure 2. - Compressor map with lines of constant turbine-inlet temperature. Flight Mach number, 0; altitude, 0; no compressor-exit bleed.

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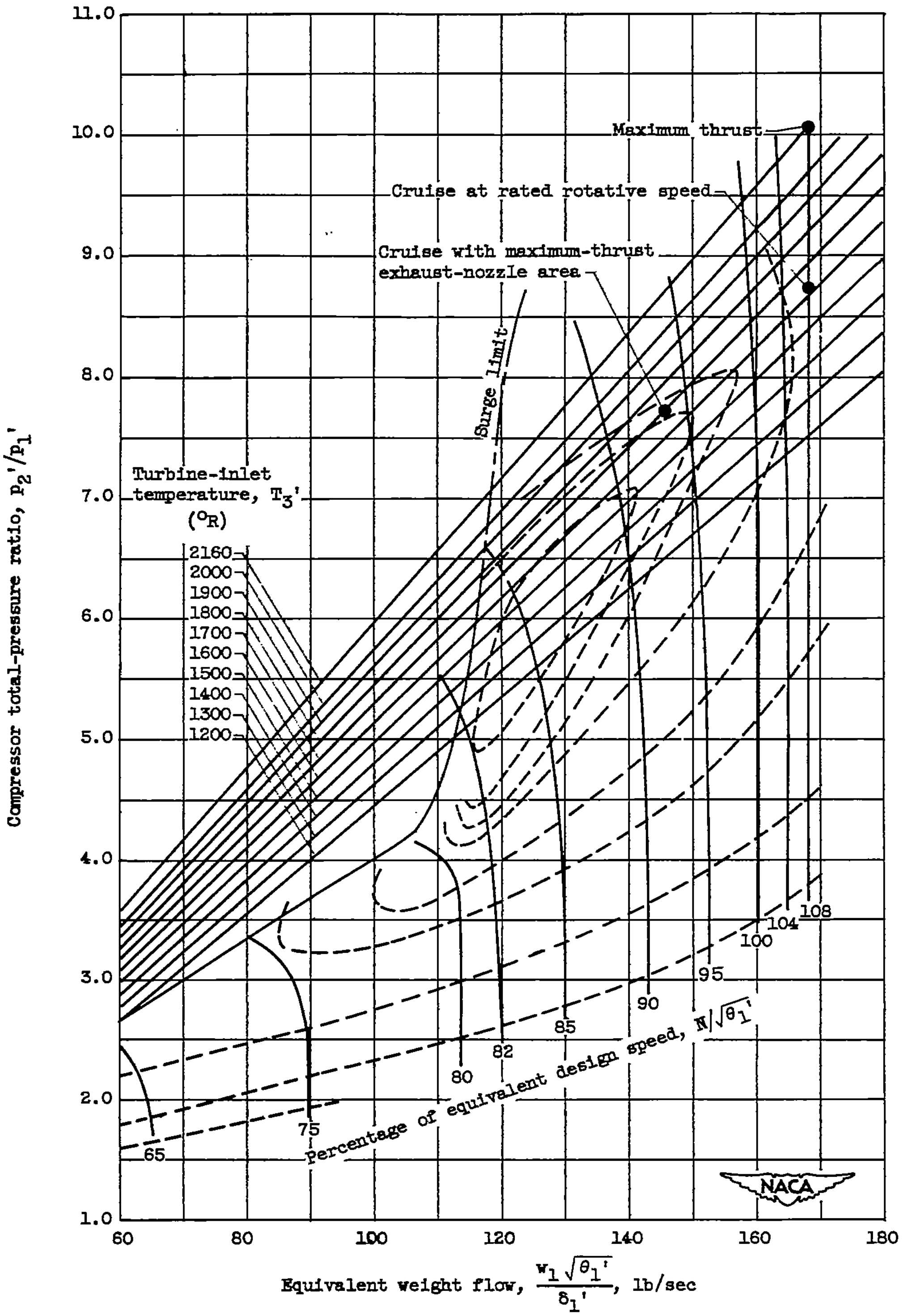


Figure 3. - Compressor map with lines of constant turbine-inlet temperature. Flight Mach number, 0.75; altitude, 35,000 feet.

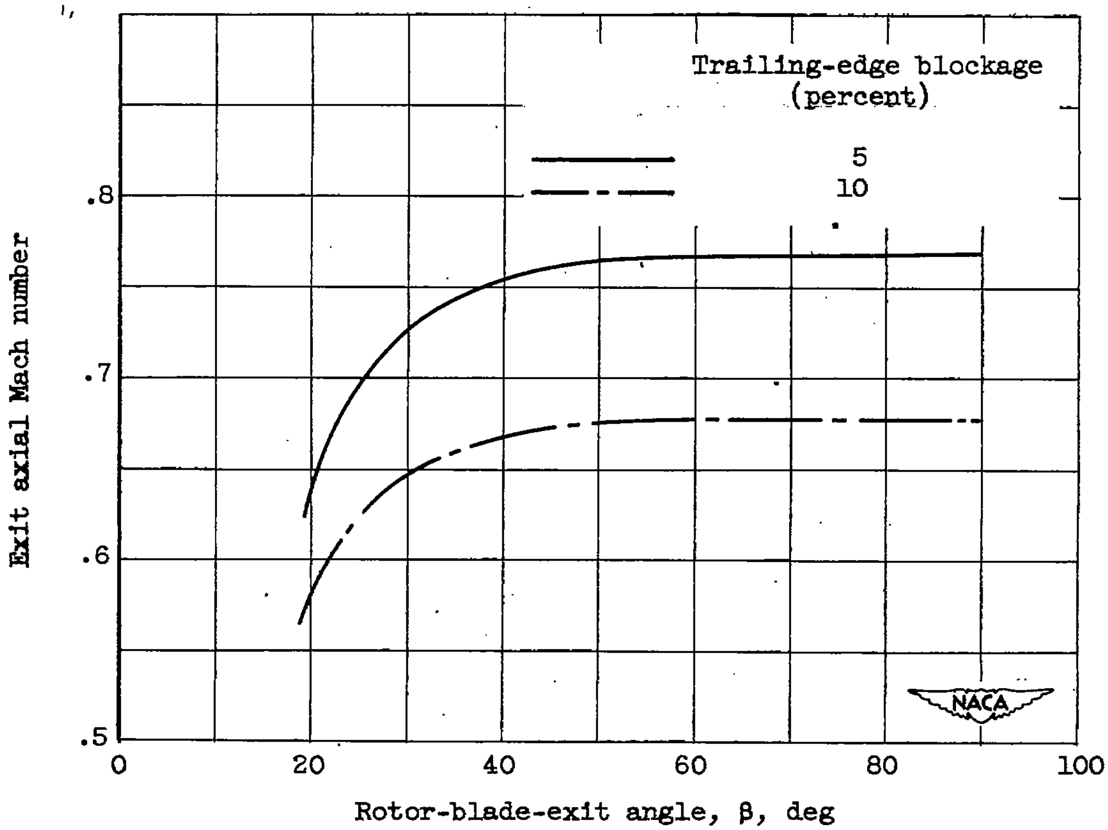
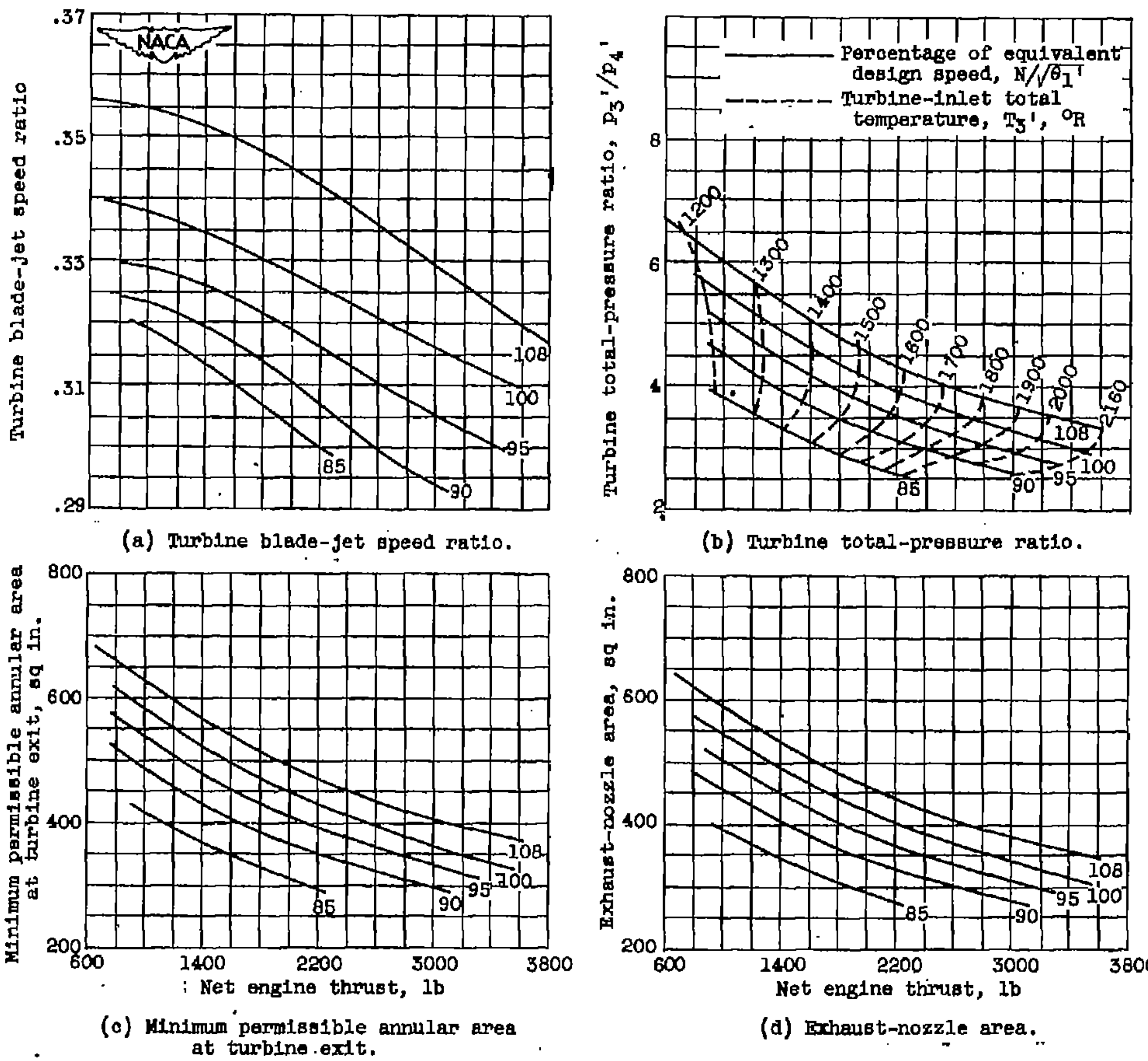


Figure 4. - Variation in exit axial Mach number with rotor-blade-exit angle and trailing-edge blockage for turbine blades at limiting loading. Ratio of specific heats, γ, 1.40.



(a) Turbine blade-jet speed ratio.

(b) Turbine total-pressure ratio.

(c) Minimum permissible annular area at turbine exit.

(d) Exhaust-nozzle area.

Figure 5. - Over-all engine performance. Altitude, 35,000 feet; flight Mach number, 0.75.

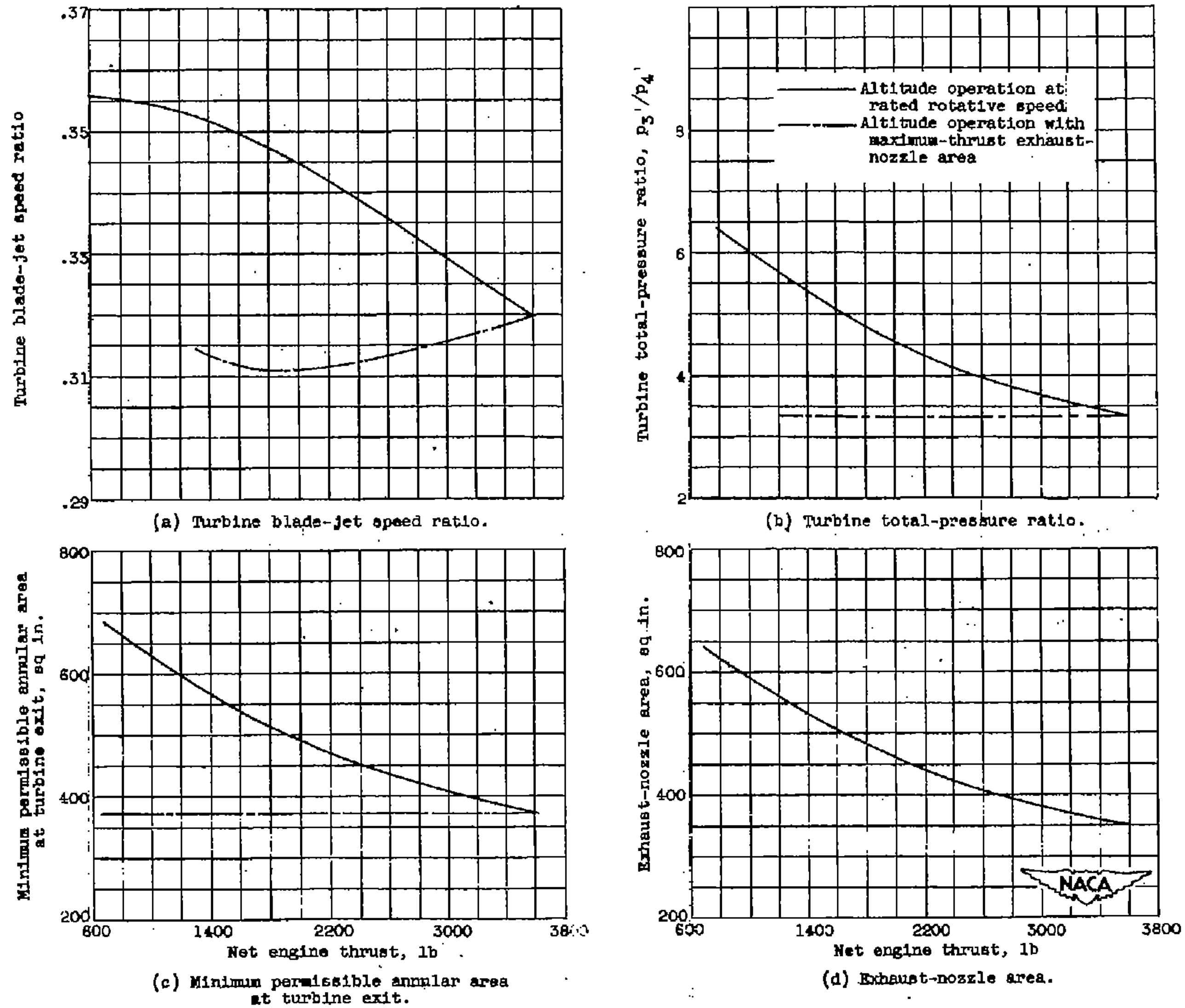


Figure 8. - Engine performance for two modes of thrust variation. Altitude, 35,000 feet; flight Mach number, 0.75.

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